End Correction of Helmcholtz Type Silencers

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Abstract

The effects of geometric parameters and a flow on the acoustical characteristics of Helmeholtz type single-resonator silencers have been investigated. It is shown that the end correction coefficient on a connector between a resonance chamber and a duct diminishes with increasing of the ratio of diameter to length of the connector and the mean flow velocity .Consequently the resonance frequency is shifted owing to the change of the resonator reactance.

1. Introduction

Helmeholtz type resonators are widely used as silencers for the purpose of reducing a peak component of noise traveling in piping systems. Therefore, in case of their acoustic design, it is the main point to accurately estimate a given peak frequency.

The fundamental equation for this type of resonators was already derived [1]., and the method for automatically changing resonance characteristics was reported in comparatively recent years [2]. However, it is difficult to say that there are sufficiently available data to predict the effective length of a connector attached to a duct, that is, the one of parameters concerned with the resonance frequency and the resonator impedance. Especially the influence of flow upon the effective length is not clear enough, though the former analyses have suggested the drops of resonator performances [3][4].

From the background mentioned above, the coefficient for the end correction at both ends of the connector has been investigated by measuring the transmission loss of single-resonator silencers, being presented in relation to the geometric parameters. Further the effect of flow on the results are shown with comments on the prediction of silencer characteristics.

2. Experimental Apparatus and Method

2. 1 Apparatus and Measurement Method

The schematic diagram of the experimental apparatus is sketched in Fig.1. The power supply to the driver unit consisted of the output of an oscillator fed through an amplifier. The pure tones conducted into the inlet duct, after passing over a test resonator, traveled in the outlet duct, and were absorbed in the nonreflection terminal formed by an involute tube with glass wool. The air flow from the blower

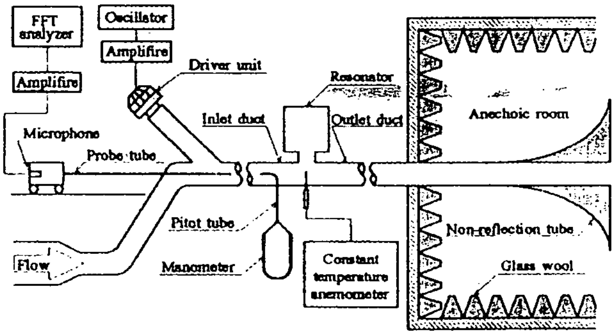
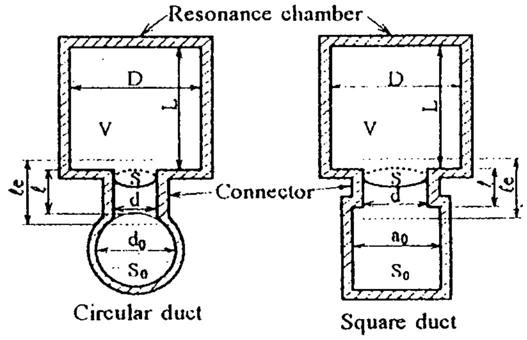


Fig.1 Schematic diagram of experimental apparatus



Circular duct

Square duct

Fig.2 Reasonators

whose noise was attenuated enough by a pre-muffler, progressing together with the sound from the driver unit, was emitted into the anechoic room.

The two kinds of duct were used as shown with the symbols in Fig.2. One was made with the circular pipe (diameter d_0=48mm), and the other was the square pipe (side length a_0=51mm). The resonator size was changed in the ranges as follows ; the diameter and the length of cylindrical resonance chamber, respectively, D=60~146mm and L=20~160mm, the connecter diameter d=20~48mm, and connector length ℓ=20~80mm.

The transmission loss characteristics were obtained from the difference between sound pressure levels measured at two phase-equaled positions before and behind a resonator, by the probe tube microphone slid along the duct wall and the FFT analyzer. In this case, the influence of the reflected waves in the inlet duct was nearly removed by using the correction chart [1]., and the difference between the maximum and minimum values of sound pressure level in the outlet duct was under 2dB at 200Hz that was the lower limit of the frequency range measured. It was verified that the sound pressure levels behind the resonators were plenty small as compared with those of flow noise generated at the resonator entrances. The flow velocity was measured up to about 50m/s by the Pitot tube.

2.2 Calculation Method and Parameters

The silencer characteristics are commonly predicted by using the one-dimensional theory, because the noise attenuation expected could be gained in the region under the critical frequency until which the plane wave should be kept. So, the transmission loss equations and the variables in those, which are shown below, have been used for the experimental analyses.

The coefficient on sound energy dissipation in the sheared fluid was obtained from the discussion on fluctuating entropy [5]. It was adopted, together with Much number, into the equations on energy, continuity and momentum, in order to estimate the muffler performances in flow ducts [6]. Munjal, by the same manner, derived the matrix in connection with the sound pressures and the mass rates which are evaluated at the connector end, and immediately before and behind a branch resonator [3]. This matrix in which the elements are denoted by Ar, Br, Cr and Dr, if the impedance is exchanged to that of the Helmeholtz type resonator, can be written as

$$\begin{pmatrix} \mathrm{Ar} & \mathrm{Br} \\ \mathrm{Cr} & \mathrm{Dr} \end{pmatrix} = \frac{1}{1+2\dfrac{MZ_0}{Zr}} \begin{pmatrix} 1+\dfrac{MZ_0}{Zr} & \dfrac{M^2Z_0^2}{Zr} \\ \dfrac{1}{Zr} & 1+\dfrac{MZ_0}{Zr} \end{pmatrix} \tag{1}$$

$$Zr = jX = j\left(\frac{2\pi f \rho_0 \ell e}{S} - \frac{\rho_0 c^2}{2\pi f V}\right) \tag{2}$$

$$Z_0 = \frac{\rho_0 c}{S_0} \tag{3}$$

where Zr is the resonator impedance expressed only by the reactance X as the viscosity effect can be neglected, Z_0 is the characteristic impedance of duct which has the same expression as in case without flow [3]., M is Mach number, and the other quantities are as follows ; c : sound velocity, ρ_0 : mean density of air, S_0 : cross-sectional area of duct, ℓe : effective length of connector, S : cross-sectional area of connector, V : volume of resonance chamber and f : frequency. The impedance in the duct with nonreflection terminals is given by Z_0 included in equation (3). Hence, let A, B, C and D be the elements of the equivalent matrix throughout the resonator-installed duct, and then

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 1/Z_0 & 1 \end{pmatrix} \begin{pmatrix} \mathrm{Ar} & \mathrm{Br} \\ \mathrm{Cr} & \mathrm{Dr} \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 1/Z_0 & 1 \end{pmatrix} \tag{4}$$

The transmission loss expression is

$$TL = 10\log\left|\frac{Z_0 C}{2}\right|^2 \tag{5}$$

The element C can be calculated from equations (1), (2), (3) and (4). Substituting the result into equation (5) gives

$$TL = 10\log\left|\frac{\left\{M(1+M)^2 + \left(\dfrac{X^2}{Z_0}\right)\right\}^2 - \dfrac{(1-M)^4}{4}\left(\dfrac{X}{Z_0}\right)^2}{\left\{4M^2 + \left(\dfrac{X}{Z_0}\right)^2\right\}^2}\right| \tag{6}$$

and if M=0

$$TL = 10\log\left|1 + \frac{1}{4}\left(\frac{Z_0}{X}\right)^2\right| \tag{7}$$

where

$$\frac{X}{Z_0} = S_0\left(\frac{f}{fr} - \frac{fr}{f}\right)\sqrt{\frac{\ell e}{S V}} \qquad (8)$$

The resonance frequency is given by

$$fr = \frac{c}{2\pi}\sqrt{\frac{S}{V\ell e}} \qquad (9)$$

Among the three parameters for determining the resonance frequency in equation (9), the connector area and the volume chamber are the real dimensions, respectively, but the effective length should empirically be obtained by

$$\ell e = \ell + \beta d \qquad (10)$$

where β is the coefficient for correcting a connector length at it's both ends. Term βd, meaning the excess length added, may be caused by mass oscillating out of the connector ends. If the value of effective length ℓe is known, the transmission loss could be calculated by equations (6) or (7), (8) and (9).

In this investigation, the value of ℓe was calculated backwards by equation (9) into which the resonance frequency given by the experimental transmission loss was substituted. Then, by using this value, the coefficient β has been obtained from equation (10). The value of β may be concerned with each shape of connector ends, the shape of connector itself and frequency. It is considered that these dimensionless parameters, when written by the said symbols, are d/D, d/d_0 or d/a_0, d/ℓ and kd, where k is the wave constant (=2πf/c).

3. Results

3.1 End Correction without Flow

The experimental characteristics of transmission loss of resonators without flow is shown in Fig.3. The experimental values have been verified by the calculations denoted by solid line. Then the values of correction coefficient β on various dimensional connectors, obtained from the method described in the previous chapter, are shown in Fig.4 and Fig.5. The coefficient β diminishes with increasing of the dimensionless frequency kd, and finally becomes constant. In this case, the numerical value of kd over which the coefficient β is unchangeable moves to the smaller region as the diameter ratio d/D is decreased. As shown in Fig.6 and Fig.7, when being independent of frequency, the coefficient β approaches the constant values as becoming small nearly irrespective of the change of the ratio d/d_0, according as the ratio d/ℓ is

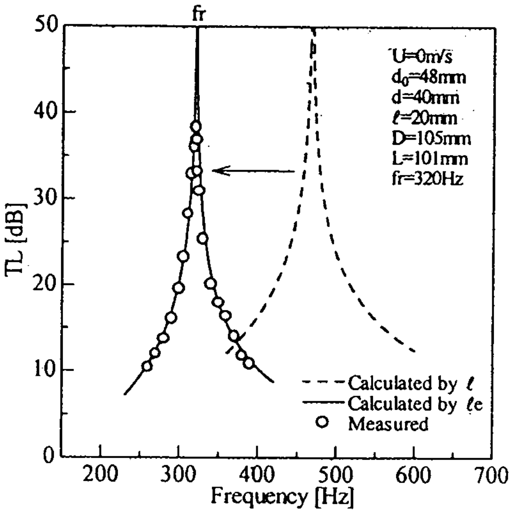


Fig.3 Transmission Loss characteristics without flow

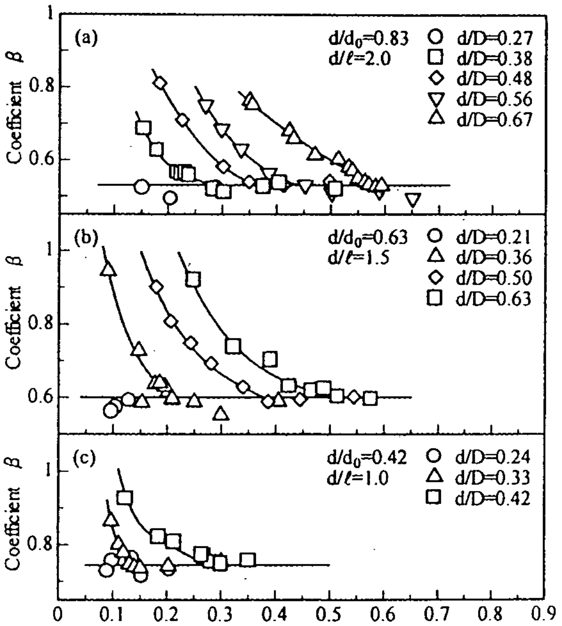


Fig.4 Relation between coefficient β and kd in circular duct

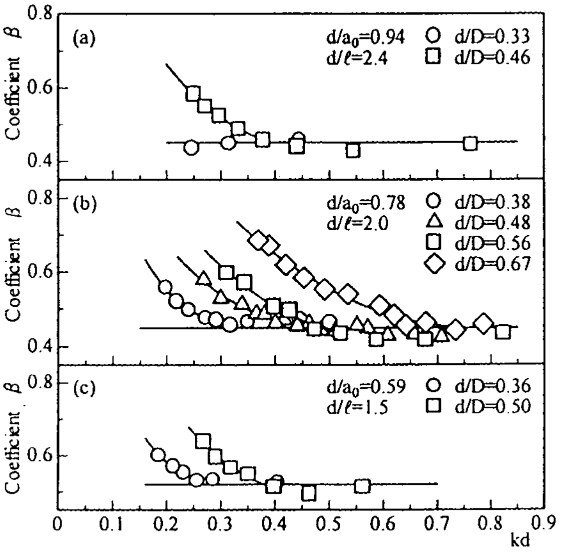


Fig.5 Relation between coefficient β and kd in square duct

increased. In this occasion, it's level in the circular duct is slightly higher than in the square one, and the errors led by the ratio d/D remain less than 0.1 at most. These facts indicate that the connector shape contributes principally to the variation of the end correction.

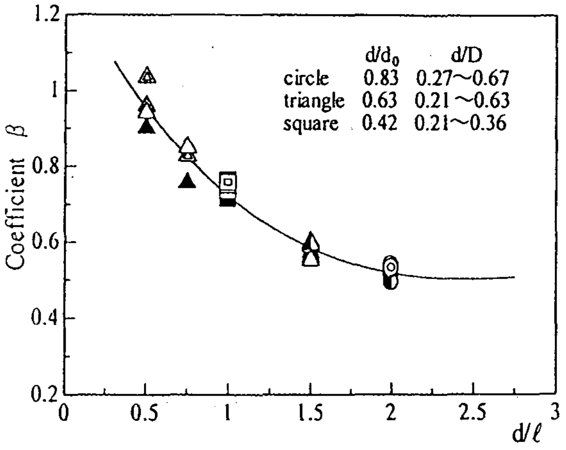


Fig.6 Relation between coefficient β and d/ℓ in circular duct

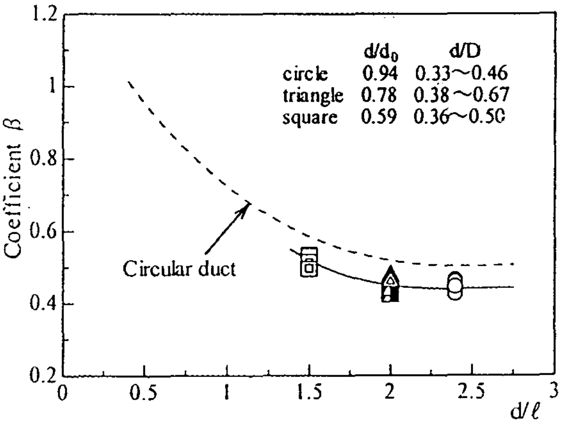


Fig.7 Relation between coefficient β and d/ℓ in square duct

3.2 End Correction with Flow

Fig.8 and Fig.9 show the transmission loss characteristics of the single-resonator silencers attached to the flow-traveling square duct. When the ratio d/ℓ is 0.5, the resonance frequency is hardly changed till the mean flow velocity U becomes about 25m/s at most (Fig.8 (a)~(d)), however, it begins to vary as U is 30m/s or so (Fig.8 (e)), and considerably shifts to higher frequency as U is 40m/s (Fig.8 (f)). On the condition that the ratio d/ℓ is 2.0, such movements of the resonance component occur at pretty lower velocity (Fig.9 (c),(d)) than in the above cases. These frequency characteristics are accompanied with the reductions of resonance functions, and the experimental values of transmission loss fairly agree with the broken lines calculated by each effective length obtained in the said manner. Then the difference between the values of coefficient β without and with flow, that is expressed by Δβ, is arranged by the Mach number in Fig.10. It is seen that the effective length becomes shorter since the coefficient β decreases according to Mach number, and the shortening rate is different among connector forms.

Next the transmission loss characteristics of the resonator with a very shallow cavity have been examined, and the data

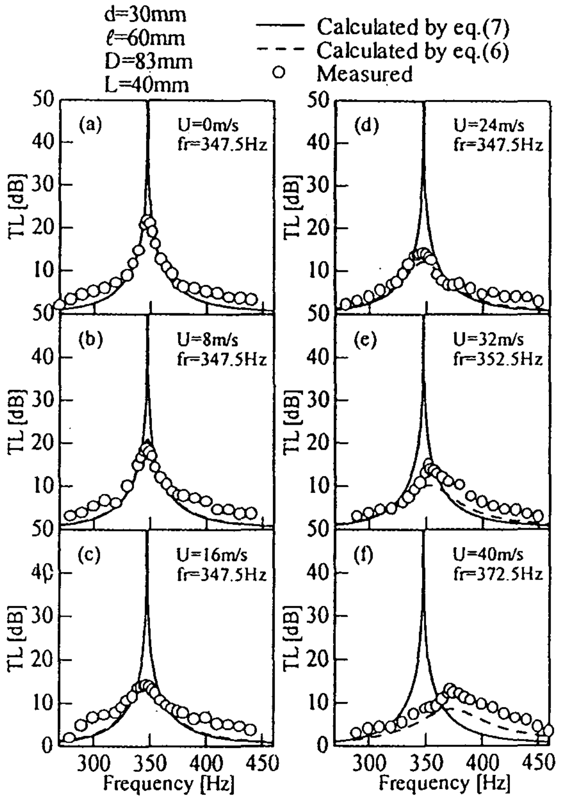


Fig.8 Transmission Loss characteristics with flow in square duct

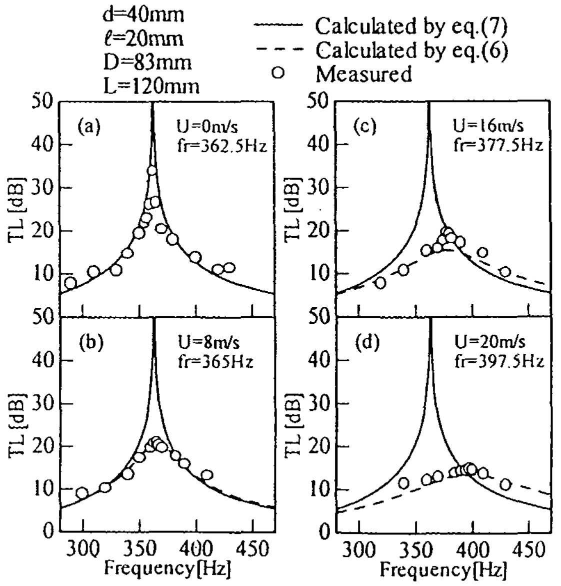


Fig.9 Transmission Loss characteristics with flow in square duct

are shown in Fig.11. When the cavity height is 5mm and U is roughly up to 15m/s, the resonance component is fixed at the similar frequency (Fig.11 (a),(b)), though that is remarkably observed in the case which has no cavity and the same velocity (compare Fig.11 (b) with Fig.9 (c)). On the other hand when h is 10mm, the resonance frequency may be little less than in case without flow till U is approximately 25m/s (Fig.11 (d),(e),(f)). These indicate that the end correction is dominated not only by the velocity of air flow, but also by the volume of air mass projected out of the connector into a flow. Therefore, it is supposed that the projected mass strained downstream is identically bent toward the connecter-attached duct wall, and its degree becomes great according to increasing of the local velocity below the connector and the length of mass entered into the flow. As a result, the effective length of the connecter may be shorten, so that the coefficient β should be estimated less than at the nonflow connector ends. As discussed above, the change of the resonance frequency with flow is brought by the effective length included in the reactance shown in equation (3), however this point has not been referred in the former works [3][4]. In addition, it is thought that the drop of resonator performances, little influenced by the momentum change by the force applied directly on the projected mass, may chiefly be due to the energy dissipation at the shear layer of flow passing over a connector, because the transmission loss level is almost regardless of the variation of cavity height as shown in Fig.11.

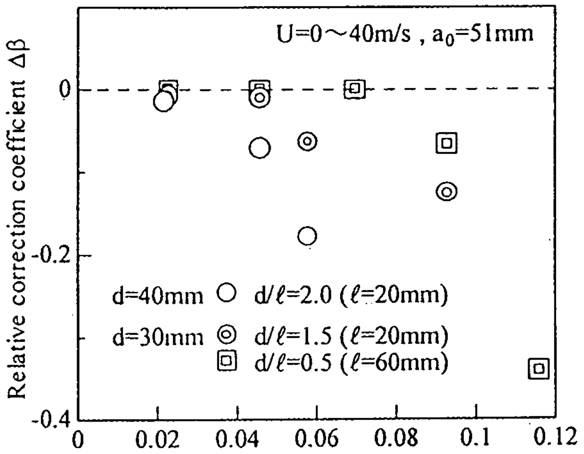


Fig.10 Effect of flow on end correction in square duct

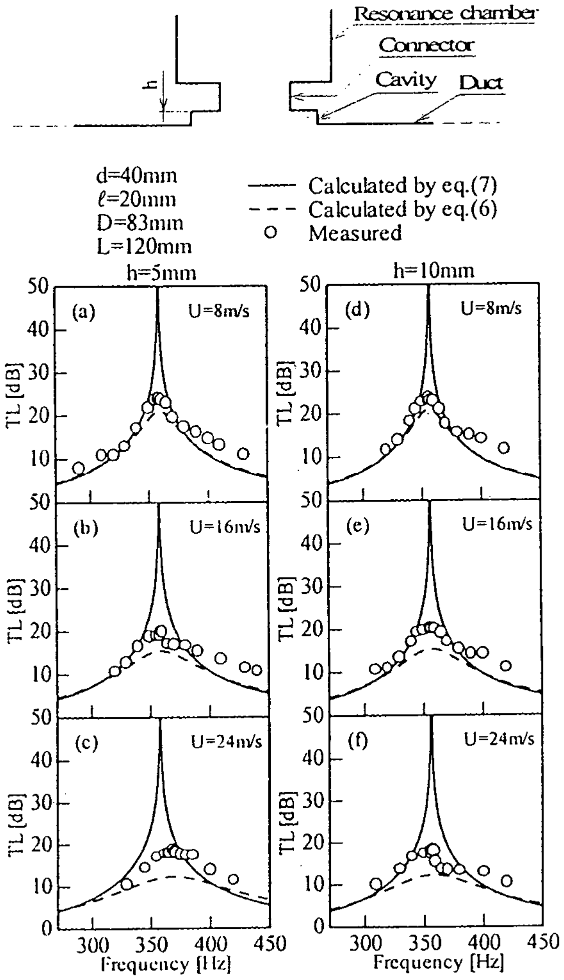


Fig.11 Transmission Loss characteristics with cavity

3.3 Comments on Prediction of Resonance Frequency

When predicted the resonance frequency for the design of single-resonator silencers, the value $\pi/4$ has been used hitherto as the end correction coefficient. This value merely corresponds to the ratio d/ℓ by nearly 0.8 as seen in Fig.6, and, hence, may not be applied to various sizes of the resonator. Thus, Fig.6 could be utilized as the chart for the resonator design, in a range of the flow velocities which have little influence on the effective connector length. On the occasion of deciding the coefficient β, if it's larger value is taken, the connector may acoustically lengthen in more degree to the effective length, because the real connector length and excess one both have to be relatively longer. In consequence, the attenuation parameter $\sqrt{SV/\ell e}$ in equation (8) may have the smaller value, and for this reason the resonance band region naturally becomes narrow. On the other side when the smaller value of β is adopted, that region inversely may widen and the experimental errors are less, so that, roughly speaking, it is better practically to make use of the larger value of the ratio $d/\ell e$ even if the flow has the effects in a great extent on the resonance frequency. But the data shown in Fig.10 is not enough in order to predict such flow effects.

4. Conclusion

The experiment was made on the end correction of the resonator type silencers. The results are summarized as follows.

(1) The coefficient β on the end correction diminishes with increasing of the ratio of diameter to length of the connector, and finally becomes constant.

(2) The resonance frequency of the resonator with flow shift to higher frequency than in case without flow, so that the coefficient β becomes smaller.

(3) The value of b in the circular duct is a little larger than in the square one.

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